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A new type of symmetric slip-friction connector

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ABSTRACT

In recent decades, there has been increasing interest in the use of slip-friction connectors (or slotted-bolt connectors) to dissipate energy in earthquake resistant structures. These devices, which rely on the friction controlled sliding of steel plates, have already seen implementation in buildings with steel moment resisting frames, with the intention that non-linear behaviour is concentrated at the connectors themselves, thereby protecting the structure from damage. The sliding mechanism of slip-friction connectors can be either symmetric or asymmetric. In the case of symmetric connectors, brass shims have, up until now, been required to ensure stable elasto-plastic behaviour. However brass can be expensive, and sometimes difficult to procure. A new type of symmetric connector that entirely eliminates the need for shims of any kind is proposed. The centre-plate of the connector consists of abrasion resistant steel that is in direct contact with the mild steel plates between which it slides. From experimental testing, the performance of the proposed connector is found to be equal, if not superior, to that of traditional symmetric connectors with brass shims. The proposed connector maintains strength and stiffness over a large number of cycles of loading, and although minor pre-conditioning of the sliding surfaces may be required in order to improve behaviour, is nevertheless simpler, and likely to be cheaper, than its current equivalent with brass shims. The potential for galvanic corrosion is also avoided.

1. Introduction

Traditionally, earthquake resistant structures have been designed to incur a limited amount of plastic deformation during a seismic event. However, recent years have seen increasing focus on the principle of 'damage avoidance', whereby non-linear behaviour occurs not through plastic deformations, but instead through the provision of energy dissipation devices at specific locations in a structure. A simple and cost effective energy dissipation device is the 'slip friction' connector, also known as the 'slotted bolt' connector. The slip-friction connector relies on the mobilisation of friction between steel plates. Non-linear behaviour occurs when the slip-threshold force, F_{slip}, is achieved (see Fig. 1) and sliding takes place. The frictional forces are mobilised by tension bolts that clamp the plates together. There are two types of slip-friction connectors, namely *asymmetric* and *symmetric*. The typical hysteretic behaviour of each is different, with the symmetric connector providing improved elasto-plastic behaviour and a more predictable sliding force (compare Fig. 1(b) with Fig. 1(a)).

Asymmetric connectors have the external loads applied to the slotted centre-plate and only one of the external plates (see Fig. 1(a)). Thus during sliding, the external plate that is not directly loaded is 'dragged' along by the bolts, and this can give rise to complex stresses on the bolts and on the bolt holes. Nevertheless, the asymmetric connector has been experimentally shown to perform well in steel moment frames [1]. Slip-friction connectors in symmetric sliding (see Fig. 1(b)) work with the connector load, F_{slip}, applied to the slotted centre-plate (as with the asymmetric connector), but with $1/2F_{slip}$ applied to each of the external plates. Provided the bolts do not impact the slot ends during earthquake excitation, there are only tensile stresses on the bolts. Brass or steel shims, 2 or 3 mm thick, (not shown in Fig. 1) are typically inserted between the mild steel plates of both asymmetric and symmetric connectors, in order to reduce wear and tear, and to enhance hysteretic stability.

Popov et al. [2] has reported that for *symmetric* connectors, mild steel sliding against mild steel tends to produce erratic and uneven force–displacement behaviour. However when 3.2 mm shims of half-hard cartridge brass are inserted between sliding surfaces, stable and rectangular hysteresis loops are obtained. These connectors were further tested in a braced structure placed under earthquake excitation on a shake-table. They were found to perform well under this heavy duty regime, and energy dissipation could readily be increased by simply increasing design ductility. However, there is the drawback that the half-hard cartridge brass required is typically expensive and not always readily available. For steel structures, Clifton et al. [1] developed the asymmetric sliding-hinge joint for use at the beam column joints of moment resisting steel frames. This concept has seen implementation in the design and construction of several steel buildings in New Zealand [3]. Butterworth [4] explored the use of asymmetric connectors in concentrically braced frames, finding from time-history analyses that even with structural ductility factors as large as 6.7 to 18.6, maximum drifts remained within code prescribed limits. Bora et al. [5] investigated the use of asymmetric slip-friction connectors with brass shims as hold-downs for pre-cast concrete walls, and found that the connectors could provide ductility to these otherwise brittle structures, and effectively

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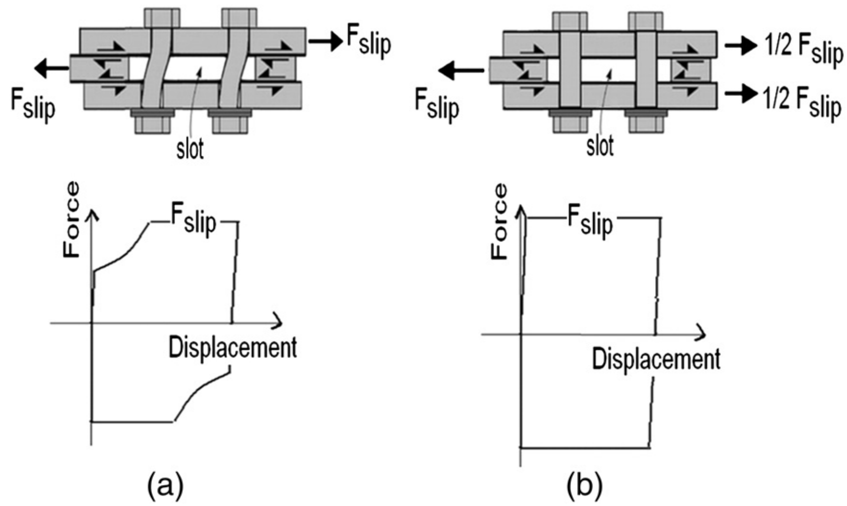

Fig. 1. Two types of slip-friction connectors and their typical hysteretic behaviours: (a) asymmetric connector, and (b) symmetric connector.

cap base shear. As expected with asymmetric slip-friction connectors, Bora's connectors showed a double plateau in their force–displacement behaviour. Bora et al. explained that the double plateau relates not to the frictional sliding characteristics of brass against steel, but instead through sliding first being initiated between the plate attached to the precast wall, and the slotted centre-plate attached to the foundation, and then followed by slip between the centre-plate and the cover plate at a slightly larger displacement. Khoo et al. [6] tested *asymmetric* connectors, with abrasion resistant steel shims replacing the previously used brass shims. It was shown that abrasion resistant steel in direct contact with mild steel could produce stable sliding, and that performance generally improved with increasing differences in hardness between the type of abrasion resistant steel used on the one hand, and mild steel on the other hand. Further to the work of Khoo et al., Chanchi Golondrino et al. [7] also demonstrated that for asymmetric connectors, abrasion resistant shim materials with hardness values on the Brinell scale of between 300 and 500 HB, consistently provide stable hysteretic behaviour. Golondrino et al., noted the interesting result that superior performance seemed to correlate with longer sliding lengths.

Loo et al. [8,9] has proposed the use of symmetric slip-friction connectors as hold-downs for timber shear walls. Walls with slip-friction connectors were numerically modelled and it was found that such walls have significant advantages over walls with traditional hold-down connectors. The slip-friction connectors are used to provide ductility to the wall system, thus capping base shear to the desired design level. Re-centring capability under various extreme earthquake events was found to be excellent [8]. This research has now moved into the experimental stage, and a symmetric slip-friction connector suitable for use in experimental shear walls is required. Given the promising results obtained for asymmetric connectors, it was decided that it would be worthwhile to test abrasion resistant steel with symmetric connectors as well — which to the author's knowledge has not been previously attempted. Additionally, it was decided to eliminate the need for shims altogether and simply have an abrasion resistant centre-plate of Bisalloy 60 or 400 sliding directly against the external plates. If it can be shown that symmetric connectors can perform well in the absence of shims, there will be two main advantages — firstly, fabrication costs will be reduced, and secondly, the fact that there are only two sliding surfaces for 'shim-less' connectors (instead of the four interfaces of connectors with shims), means that there is less opportunity for the ingress of constituents that could cause corrosion. Because Butterworth [4] has mentioned that previous researchers had found some success with brake-lining in friction devices, it was decided that it would also be worthwhile to try this concept on an exploratory basis. Based on the results of the exploratory tests, one of either abrasion resistant steel, or brake lining, would be chosen for comprehensive experimentation.

This paper describes research that attempts to address the following main themes:

1. The feasibility of using brake lining in symmetric slip-friction connectors.
2. The feasibility of using abrasion resistant steel for the centre-plate, and avoiding the need for shims altogether.
3. The hysteretic performance of different grades of abrasion resistant steel.
4. The effect of rate of loading on hysteretic behaviour.
5. The effect of surface preparation on hysteretic behaviour.

2. Exploratory investigations into brake lining and abrasion resistant steel

Two symmetric slip-friction connectors were fabricated for testing in the MTS machine. One of the connectors used brake lining to facilitate sliding, while the other connector had no shims whatsoever, with sliding taking place between the centre-plate of abrasion resistant steel and the mild steel external plates. Based on the results of these tests, one of these options would be later explored in greater detail.

It should be emphasised that because only one specimen was used to explore each of the two concepts, the results for these exploratory tests should not be interpreted as providing any sort of definitive conclusion on the feasibility or non-feasibility of either option. The tests were conducted simply to suggest the likely superior option for further detailed testing. Nevertheless, for the reader's interest, a brief discussion is provided of these exploratory investigations.

2.1. Exploratory investigations: connector configuration and test setup

The general configuration of the two symmetric connectors was essentially the same and is shown in Fig. 2(a). The only difference between the two connectors was one had brake lining glued to the inside surface of the two external plates while the other used Bisalloy 400 (an abrasion resistant steel) for the slotted centre-plate. For the latter connector, because no shims were used, the Bisalloy 400 was in direct contact with the mild steel of the external plates. Bolts were maintained in tension by Belleville washers. Fig. 2(b) shows the displacement schedule used for the tests, and Fig. 2(c) shows the connector with brake lining, set up in the MTS machine.